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EP 0270862 A

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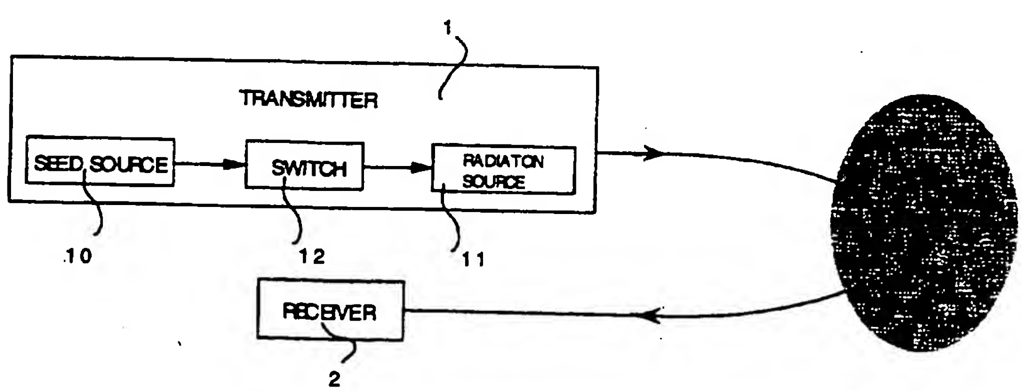
(54) Remote survey of trace gases

(57) Equipment for remote survey of trace gases, eg using Differential Absorption Lidar (DIAL), comprises a transmitter (1) of variable spectral hand width and a receiver (2). The transmitter comprises a seed source (10), a radiation source (11), and a switch (12) which is arranged therebetween and by means of which the radiation source (11) is switchable between seeded (narrow band) operation during which radiation is delivered at the absorption frequency and unseeded (wide band) operation during which radiation is delivered at a reference frequency. The receiver detects backscatter signals due to the narrow band and wide band operations and arriving from two distances to determine the absorbtion in the region between those distances. The narrow band should be narrower than the absorption line of the gas to be detected and tunable to that absorption line. A continuous or pulsed laser and an optical parametric oscillator may be used.

Fig.1



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At least one drawing originally filed was informal and the print reproduced here is taken from a later filed formal copy.

Fig.1

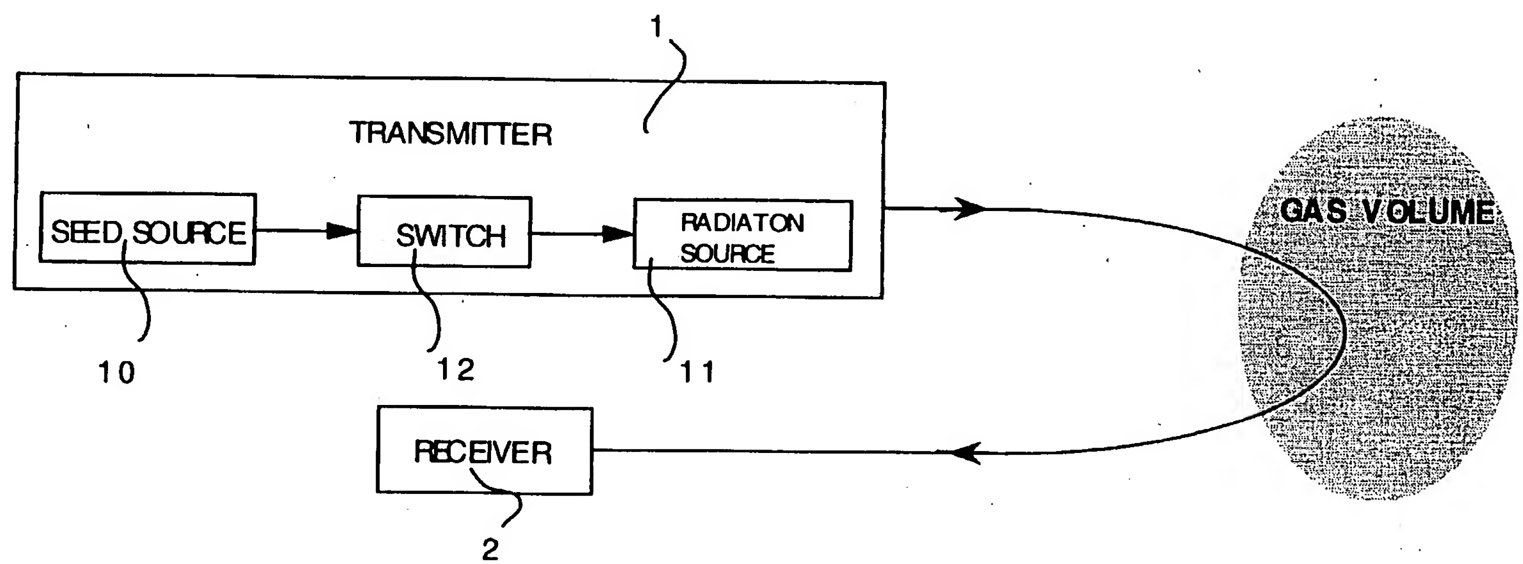

TRANSMITTER
1
SEED SOURCE
SWITCH
RADIATON SOURCE
10
12
11
RECEIVER
2
GAS VOLUME

Fig.2

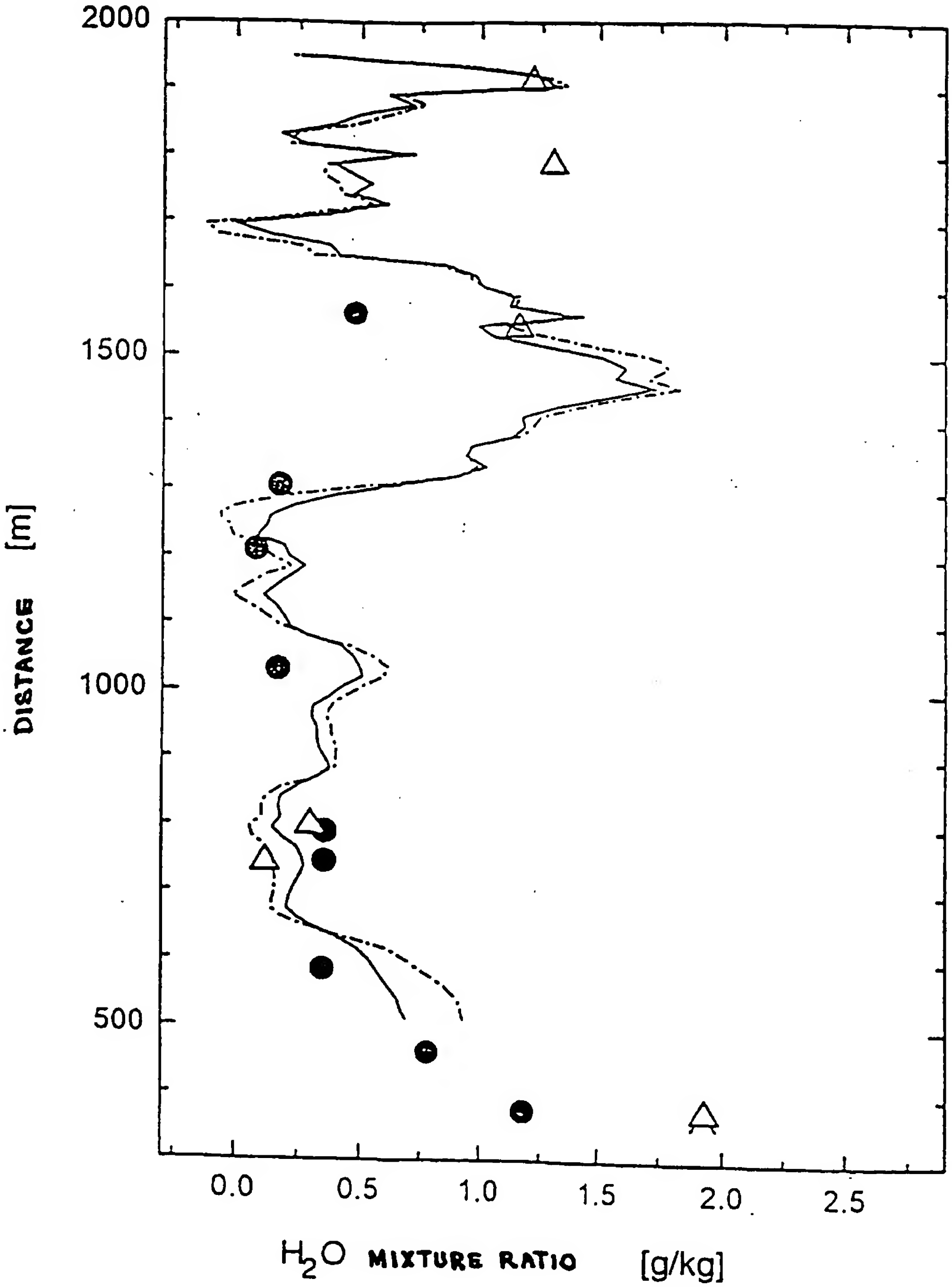

2000
1500
1000
500
0.0
0.5
1.0
1.5
2.0
2.5
DISTANCE [m]
H_2O MIXTURE RATIO [g/kg]

Fig.3a

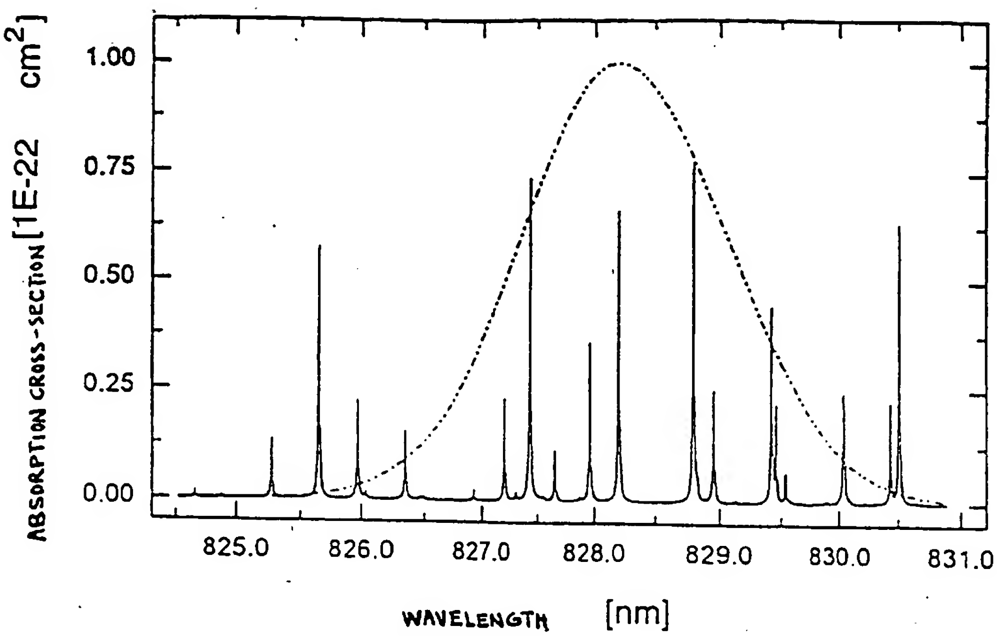
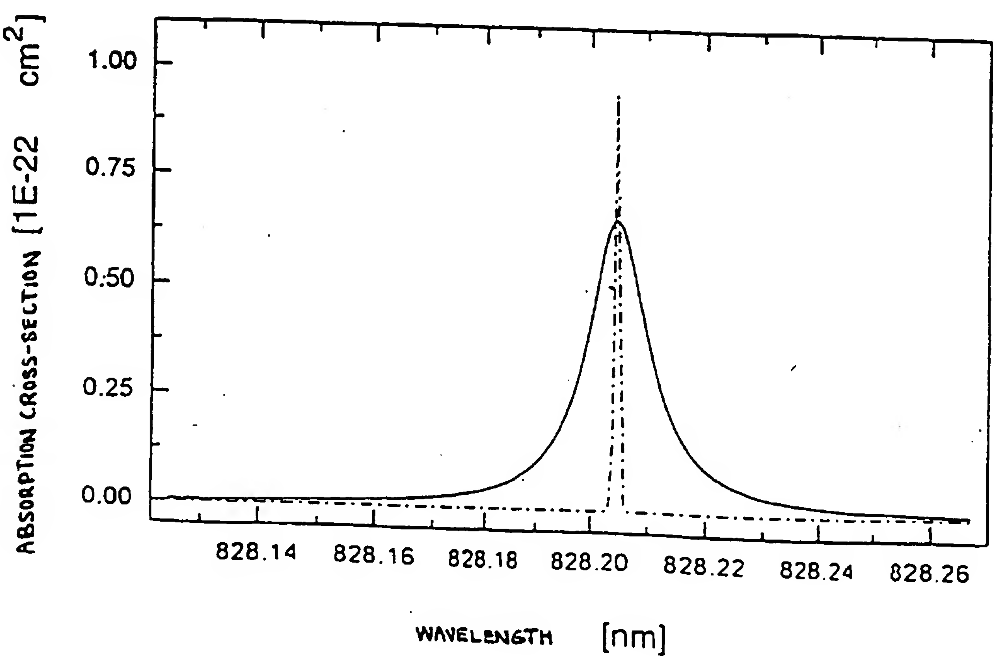

ABSORPTION CROSS-SECTION [1E-22 cm2]
1.00
0.75
0.50
0.25
0.00
825.0
826.0
827.0
828.0
829.0
830.0
831.0
WAVELENGTH [nm]

Fig.3b


ABSORPTION CROSS-SECTION [1E-22 cm2]
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0.75
0.50
0.25
0.00
828.14
828.16
828.18
828.20
828.22
828.24
828.26
WAVELENGTH [nm]

Fig.4

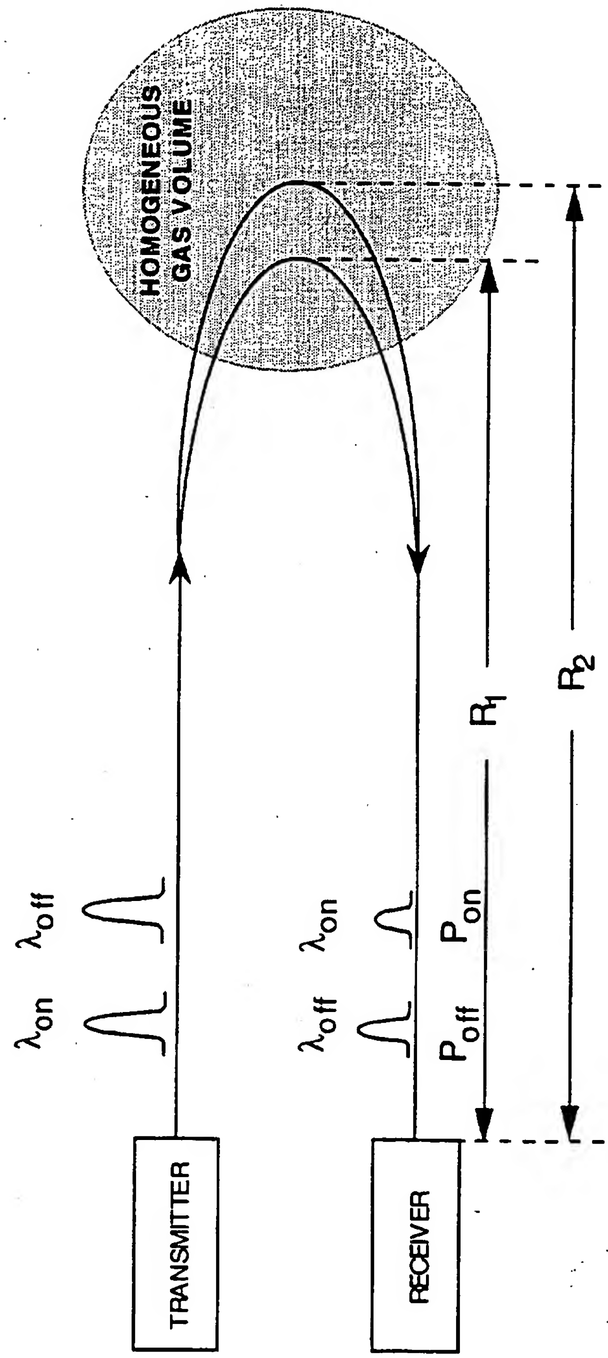

HOMOGENEOUS
GAS VOLUME
TRANSMITTER
RECEIVER
λ_{on}
λ_{off}
λ_{off}
λ_{on}
P_{off}
P_{on}
R_1
R_2

Fig.5

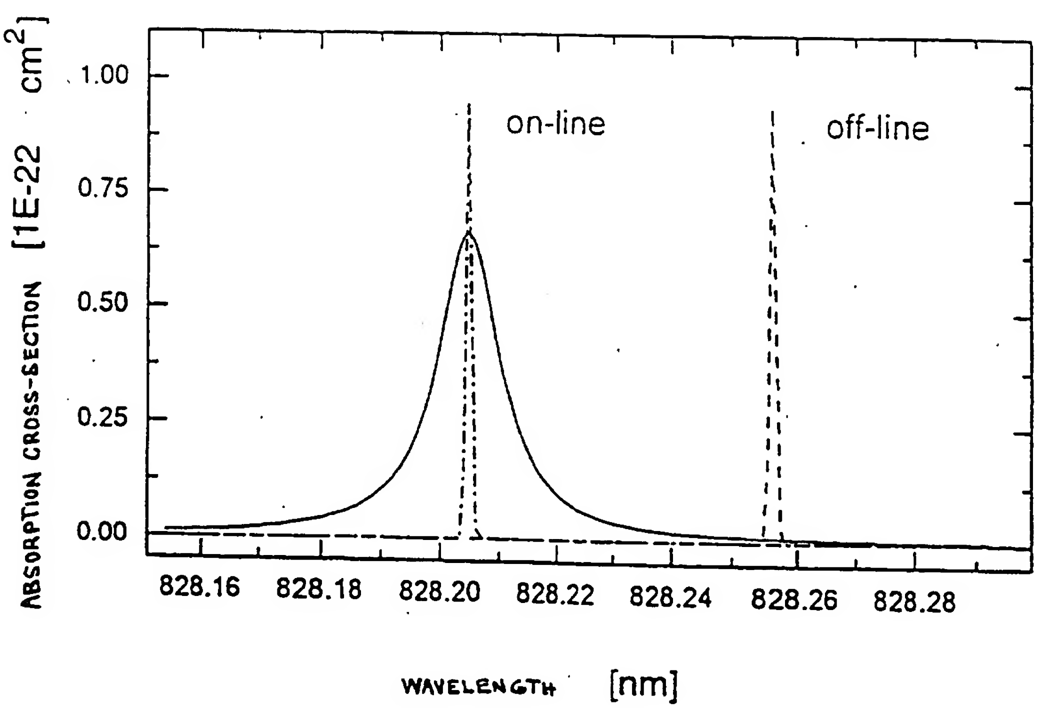

ABSORPTION CROSS-SECTION [1E-22 cm²]
1.00
0.75
0.50
0.25
0.00
on-line
off-line
828.16
828.18
828.20
828.22
828.24
828.26
828.28
WAVELENGTH [nm]

Fig.6a

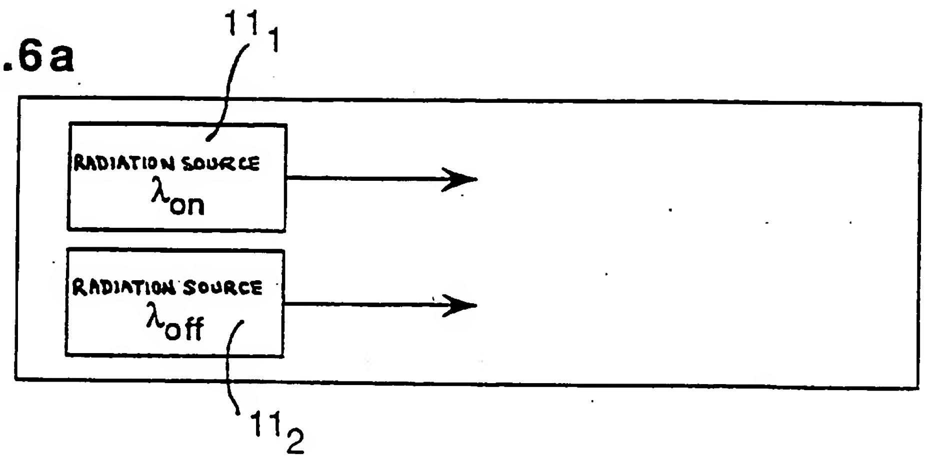


Fig.6b

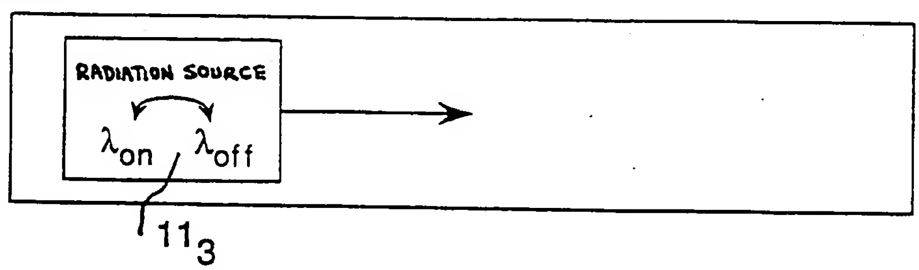


Fig.6c

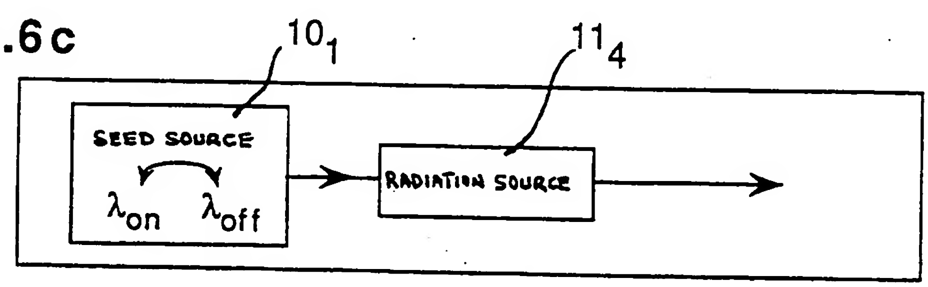
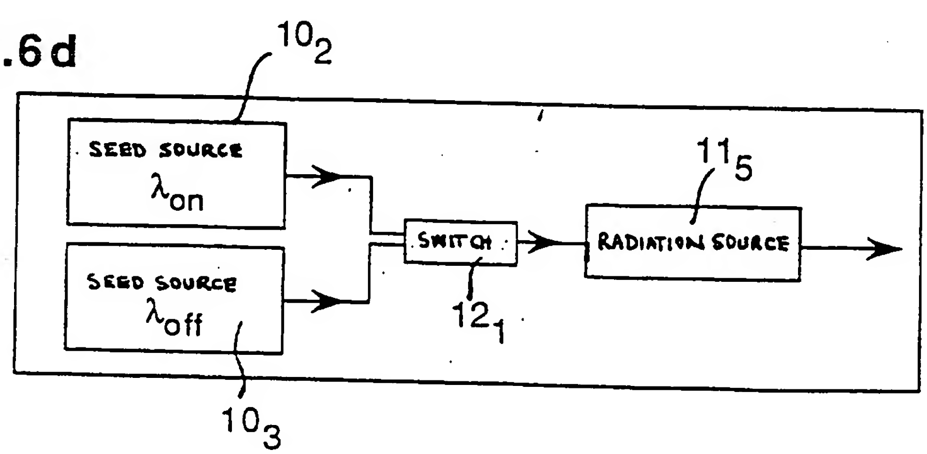


Fig.6d



METHOD AND EQUIPMENT FOR REMOTE SURVEY OF TRACE GASES

The present invention relates to a method and equipment for remote survey of trace gases, in particular with use of the DIAL method.

The DIAL (Differential Absorption Lidar) method is a further development of the conventional Lidar measuring technique, which has its origin in radar technology. Since Lidar instruments operate similarly to radar installations, they comprise a transmitter which issues pulsed electromagnetic radiation into the atmosphere and a receiver which registers the intensity of the echoes of the radiation as a function of transit time. The transit time of the pulse is a measure of the distance of a target. Measuring can, in general, be carried out very accurately by a Lidar method, since the typical time length of a pulse of the radiation source is only a few nanoseconds.

Whereas the wavelength of emitted radiation in the case of radar is in the centimetre range, a Lidar instrument emits comparatively short-wave radiation in the optical spectral range. Because of the short wavelength, this radiation interacts with the smallest components of the atmosphere, i.e. air molecules and suspended particles (aerosols), so that even clear, cloud-free air produces a detectable echo, which is not the case for radar. The intensity of the Lidar echo is then a measure of the density and optical properties of the scattering air volume as well as of the transmissibility of the atmosphere at the wavelength of the transmitter.

A number of parameters, which are meteorological or relevant to the environment, of the examined atmosphere can be derived from the backscatter data of a Lidar instrument and different techniques have been

developed in dependence on the particular objective. A measurement technique by the DIAL method is particularly suitable for remote survey of trace gas profiles.

The principle of the DIAL method is illustrated in Fig. 4. By contrast to a conventional backscatter Lidar method, which transmits at a fixed wavelength, two closely adjacent wavelengths λ_{on} and λ_{off} are emitted briefly one after the other in the DIAL method. With the wavelength λ_{on}, the trace gas absorption causes an additional attenuation of the radiation during passage through the atmosphere. The wavelength λ_{off} is the associated reference wavelength, which is chosen so that a significantly lower absorption takes place. In the case of known molecular absorption cross-sections, the trace gas profile can be computed as a function of distance in direction of propagation of the transmitter by the DIAL equation:

$$\overline{N}(R) = \frac{1}{2 \cdot \Delta\sigma \cdot \Delta R} \ln \frac{P_{off}(R_2) P_{on}(R_1)}{P_{on}(R_2) P_{off}(R_1)} \qquad (1)$$

wherein

$$\Delta\sigma = \frac{\int_0^\infty \sigma(\upsilon)[L(\upsilon - \upsilon_{on}) - L(\upsilon - \upsilon_{off})]d\upsilon}{\int_0^\infty L(\upsilon)d\upsilon} \qquad (2)$$

In this case, $\overline{N}(R)$ is the mean particle number concentration (the number of molecules per cubic metre) at a distance $R = R_1 + \Delta R/2$. The averaging relates to the distance interval $\Delta R = R_2 - R_1$ in Fig. 4, which at the same time defines the local resolution of the trace gas profile along the transmitter. The backscatter signals received from the distances R_1 and R_2 are denoted by, respectively, P_{on} and P_{off}. The

detection sensitivity is fixed substantially by the magnitude of the effective differential absorption cross-section $\Delta\sigma$ in equation (2). This cross-section is a function of the molecular absorption cross-section $\sigma(\nu)$ of the spectral energy distribution $L(\nu)$ of the spectral source, wherein ν is the frequency of the selected spectral line of the measuring trace gas.

Under atmospheric conditions, these spectral lines are, in general, widened by pressure or Doppler effect with line widths of 0.08 per centimetre (HWHM - Half Width at Half Maximum - half half-value-width) in the lower troposphere and 0.02 per centimetre in the stratosphere. The shape of the line is a Voigt profile. With the aid of the line parameters which are measured in the laboratory, the absorption cross-sections can be computed with sufficient accuracy as function of the frequency.

Fig. 5 illustrates a conventional DIAL method. In this case, the wavelength in nanometres is entered on the abscissa and the absorption cross-section [1E - 22 square centimetres] is entered on the ordinate. As example, an absorption line, which lies at 828.215 nanometres, of molecular water vapour is shown. For the on-line measurement, a narrow-band transmitter with $\Delta\nu_{transmitter}$ very much less than $\Delta\nu_{molecule}$ was tuned to the line centre of a linear transition. The off-line measurement took place in the line wing with a negligible absorption. In the case of a narrow-band (monochromatic) radiation source with $\Delta\nu_{transmitter}$ very much less than $\Delta\nu_{line}$, as illustrated in Fig. 5 for a transmitter with $\Delta\nu_{transmitter}$ very much less than $\Delta\nu_{molecule}$, the equation (2) can be evaluated simply as

$$\Delta\sigma = \sigma_{on} - \sigma_{off}, \tag{3}$$

wherein σ_{on} and σ_{off} represent the absorption cross-section in the line centre (on-line) or in the line wing (off-line). As already explained, σ_{on} is generally very much greater than σ_{off}, so that the differential absorption cross-section of the DIAL equation is given essentially by the value of the line centre, whereby the evaluation is appreciably simplified.

The range of possibilities of use of a DIAL system in the monitoring of the environment and the climate is substantial. Fixed systems on the ground as well as aircraft-borne instruments have been used with success to, for example, measure distributions of ozone, nitrogen oxide and water vapour in the atmosphere. As theoretical examinations have shown, the DIAL technique could, for example, be applied from outer space - with a satellite as a platform - for global examinations.

Moreover, it has been established by the applicants that this measurement technique is very robust and has relatively little sensitivity to pressure and temperature changes in the atmosphere or changes in the detection sensitivity. Since the DIAL method is, in principle, a self-calibrating measurement technique, complicated calibration measurements are not necessary in order to detect a trace content quantitatively. This method is thus clearly distinguished from passive methods in which the sensitive radiation power must be measured quantitatively in order to derive a trace gas profile. In addition, the DIAL method, which can be used during day or during night, has a significantly higher distance resolution than the passive methods.

In spite of these merits of the DIAL method, there are still only a

few operational DIAL instruments. The reason for this lies in the complexity of the systems, in particular the transmitter. As a transmitter for realisation of a DIAL method predominant use has been of a continuously tunable pulsed laser system, which due to low beam divergence and to energy can achieve high illumination intensities at greater distances so that an echo is detectable. Continuous tunability is necessary so that the wavelength, in the case of an on-line measurement, can be tuned exactly to the line centre of a molecular transition of the trace gas to be measured. The maximum permissible pulse energy of the transmitter is, in the case of the Lidar method, usually limited so as to provide protection for the eyes. A high spatial or time resolution of the measurement therefore requires the highest possible pulse repetition frequencies.

In general, one of the following variants is used in conventional DIAL systems:

a) Two narrow-band radiation sources 11_1 and 11_2, of which one (11_1) is tuned to the on-line wavelength λ_{on} and the other (11_2) to the off-line wavelength λ_{off} (see Fig. 6a). The two radiation sources must fulfill high demands on energy, mean power, beam divergence and spectral properties. When two beam sources 11_1 and 11_2 are used, the instrument construction and the total weight are comparatively high. Moreover, the two beam sources 11_1 and 11_2 must be supplied with energy and at the same time with coolant.

If the divergence of the beam sources 11_1 and 11_2 differs or if they do not emit exactly colinearly, then the examined gas volume is different for the on-line and the off-line measurements. Deviations in the region

of few fractions of milliradians lead to appreciable measurement errors so that a high degree of mechanical and thermal stability is required, which can be ensured only by a high technical effort. A compact and robust construction, which is required for mobile DIAL systems, can be realised only with constraints.

A device for aircraft-supported remote survey of trace gases with the afore-described variant of the DIAL method has been proposed in EP 0 489 546 A2. At least two continuously tunable lasers in the infrared spectral range are provided as beam sources, in particular pulsed Nd:YAG lasers, Nd:YLF lasers, Nd:Glass lasers, Ti:Sapphire lasers, Er:YAG lasers or Alexandrite lasers. For the production of narrow-band radiation, at least two continuously tunable diode lasers with a wavelength of 810 nanometres or 1550 nanometres are used. These diode lasers serve as seed lasers for optical parametric oscillators which have a pump wavelength of 532 nanometres or 1064 nanometres.

Thus, two or more different beam sources are always required. Moreover, no variable line width of the beam sources is provided, i.e. the proposed DIAL method is not based on a variable spectral width. Furthermore, the wavelength range of the equipment is restricted explicitly to the infrared spectral range.

In "Laser remote sensing of atmospheric ammonia using a CO_2 Lindar system" by A.P. Force et al in Applied Optics, Volume 24, No. 17 of 1 September 1985, pages 2837 to 2841, the variant, which has been outlined above under a), of a conventional DIAL method for remote survey of NH3 is described. Two different pulsed CO_2 lasers with a wavelength of 10.6 micrometres serve as beam sources for the production of on-line or off-line frequencies. Since the CO_2 lasers are gas lasers, their spectral

width is small (here 0.1 per centimetre), i.e. not variable, as the two beam sources employed have a narrow band. Moreover, two different beam sources must be used and a light source with non-linear frequency conversion is not involved in the case of the laser-active medium CO_2.

b) In the second variant, a single narrow-band beam source 11_3 is used, the wavelength of which is tuned back and forth at high frequency between on-line (λ_{on}) and off-line (λ_{off}). In that case, the significant disadvantages of the variant (a) are avoided. A difficulty, however, arises in that the spectral properties of the beam source do not change during retuning. A high reproducibility of the absolute wavelength and the spectral width is required for the on-line and for the off-line wavelengths.

In order to tune a beam source, which is usable for the performance of the DIAL method, between two wavelengths, two different methods can be used. In the case of the first method, frequency-selective elements, for example grids, etalons, prisms, lyot filters and the like can be used in the resonator. Due to the high demands on reproducibility, these elements must be driven and regulated with very high precision (see Fig. 6b). This can be realised only with great technical effort, particularly in the case of high pulse repetition frequencies. Moreover, elements housed internally in the resonator reduce the efficiency of the beam source. Due to the high power density in the resonator, the internal elements housed in the resonator are subjected to appreciable loads and must have a high optical destruction threshold.

In the second method (Fig. 6c) the technique of "injection seeding" is used. In this method, light from an external, narrow-band light source, a seed source 10_1, is coupled into the resonator of a beam source

11_4. It is in that case possible even with small light powers to reliably influence the spectral properties of the DIAL beam source.

It is advantageous in this technique that the checking of the spectral properties of the beam source is transferred to a separate light source. The beam source therefore only still produce the necessary optical power. Thus, its construction can be much simpler and at the same time this leads to an increase in efficiency.

A change in the wavelength λ from on-line (λ_{on}) to off-line (λ_{off}) is effected by the wavelength of the seed source 10_1 being retuned appropriately, as evident from Fig. 6c. Although this is easier to handle in view of the significantly lower mean power of the seed source than in the case of a narrow-band, continuously tunable beam source, the technical demands are nevertheless appreciable. In addition, it makes matters more difficult that the resonator of the beam source and the frequencies of the seed radiation must be tuned to each other and that the geometry of the seed radiation should not change during the retuning.

In "Injection-seeded alexandrite ring laser: performance and application in ab water-vapour differential absorption lidar" by V. Wulfmeyer et al in Optics Letters, Volume 20, No. 6 of 15 March 1995, pages 638 to 640, the DIAL method outlined in the preceding paragraph is used for remote survey of water vapour profiles in the atmosphere. A pulsed $Cr:BeAl_2O_4$ laser (alexandrite laser) with a wavelength of about 730 nanometres, which is seeded by means of a titanium-sapphire-laser, serves as a beam source. A narrow-band operation is thereby achieved. For switching back and forth between an on-line and an off-line frequency, the frequency of the titanium-sapphire laser is changed appropriately. In this form of the DIAL method, the spectral width is

always small (less than 5.10^{-3} per centimetre), i.e. not variable, since the beam source is always seeded. Moreover, the frequency of the seed source must be changed.

However, as shown in Fig. 6d, two seed sources 10_2 and 10_3 can be used for the on-line and the off-line wavelengths λ_{on} and λ_{off}, respectively. In this case, care must be taken, by means of a switching mechanism 12_1 with the correct repetition frequency, that the beam source transmits at the respective seed wavelength, as indicated schematically in Fig. 6d. Apart from this switching mechanism, a higher instrument effort caused by the provision of two seed sources is of disadvantage here.

There is therefore a need for a method and equipment for remote survey of trace gases, wherein the method may entail less effort and be appreciably simpler and thereby more rapid to perform and wherein the equipment may be significantly simpler with respect to the instrument outlay and also involve appreciably lower technical requirements.

According to a first aspect of the present invention there is provided a method for remote survey of trace gases, comprising the steps of

a) determining the particle number concentration N(R) of a gas to be examined as a function of distance ($R = R_1 + R/2$) by means of the Differential Absorption Lidar (DIAL) equation:

$$\overline{N}(R) = \frac{1}{2\cdot\Delta\sigma\cdot\Delta R}\ln\frac{P_{off}(R_2)P_{on}(R_1)}{P_{on}(R_2)P_{off}(R_1)}$$

wherein ΔR is the distance interval from the difference between two distances R_1 and R_2, $P_{on}(R_1)$, $P_{off}(R_1)$, $P_{on}(R_2)$ and $P_{off}(R_2)$ are the

powers of backscatter signals received from the distance R_1 and R_2, and $\Delta\sigma$ is the effective differential absorption cross-section calculated as

$$\Delta\sigma = \frac{\int_0^\infty \sigma(\upsilon)[L(\upsilon - \upsilon_{on}) - L(\upsilon - \upsilon_{off})]d\upsilon}{\int_0^\infty L(\upsilon)d\upsilon}$$

wherein ν is the frequency of a selected spectral line of the gas, ν_{on} is the frequency of the absorption line thereof, ν_{off} is a reference frequency, $\sigma(\nu)$ is the molecular absorption cross-section and $L(\nu)$ is the spectral energy distribution of a radiation source,

b) producing the power value P_{on} by means of radiation of a narrow-band radiation source with the absorption line frequency ν_{on} of the gas, the spectral width of the narrow-band source being less than the line width of the absorption line, and

c) producing the power value P_{off} by radiation of a wide-band radiation source of the reference frequency ν_{off}, the spectral width of the wide-band source being greater by a multiple than the line width of the absorption line.

According to a second aspect of the invention there is provided equipment for carrying out the method of the first aspect of the invention, the equipment comprising transmitting means of variable spectral band width, the transmitting means comprising a seed source, a radiation source and switching means arranged therebetween and operable to switch the radiation source between seeded, narrow band operation for delivery of radiation at the absorption frequency and unseeded, wide band operation for delivery of radiation at a reference

frequency, and receiving means for receiving backscatter signals from two distances.

It is particularly advantageous that the values, which are needed for the computation of the two equations, of the powers P_{on} and P_{off} are obtained from backscatter signals received from two distances R_1 and R_2 by the value of P_{on} being produced by means of radiation from a narrow-band beam source with the absorption line frequency ν_{on} of the gas, the spectral width of which is smaller than the line width of the absorption line, and the value P_{off} being produced by radiation of a wide-band beam source of the reference frequency ν_{off}, the spectral width of which is greater by a multiple than the line width of the absorption line. By comparison with the afore-described conventional method, only one beam source of variable spectral width is used. This is achieved with the aid of injection seeding, in which the beam source is switched between seeded, i.e. narrow-band operation, and unseeded, i.e. wide-band operation.

Only a single seed source and a single beam source are required for the operation. Thus, an adjustment with respect to overlapping of two beams is superfluous and only one beam source has to be supplied with electrical energy and a coolant.

Since only a relatively low-power seed source and a relatively simply constructed beam source typical for systems with injection is required, a light, compact and robust construction of equipment for the performance of the method is possible. Moreover, the seed source is operated at a fixed frequency in the case of the on-line wavelength. Since a change in wavelength, as hitherto, from on-line to off-line is

not required, the necessary frequency stability of the seed source can be achieved relatively simply and it is possible, without problems, to carry out operation with higher pulse repetition frequencies.

Examples of the method and embodiments of the equipment will now be particularly described with reference to the accompanying drawings, in which:

Fig. 1 is a diagram of equipment embodying the invention;

Fig. 2 is a diagram showing experimentally ascertained water vapour profiles;

Figs. 3 and 3b are diagrams illustrating aspects of a method exemplifying the invention, by the example of a water vapour spectrum;

Fig. 4 is, as already indicated, a diagram showing conventional equipment used in a DIAL measuring technique;

Fig. 5 is, as already indicated, a diagram illustrating the conventional DIAL method; and

Figs. 6a to 6d are, as already stated, diagrams showing different devices for the performance of a conventional DIAL measuring technique.

Referring now to the drawings there is shown in Fig. 1 a transmitter 1 and a receiver 2 in equipment for the performance of a DIAL method exemplifying the invention. The transmitter 1 essentially comprises three components, namely a seed source 10, a beam source 11 and a switch 12, which is arranged therebetween and interrupts the injection seeding. The beam source 11 must be so designed that it can be tuned in the range of the absorption lines of a gas to be examined. Moreover, it must have a spectral width which is greater by a multiple than that of the

absorption lines and the spectral properties of the beam source must be controllable with the aid of the injection seeding.

In addition to the spectral properties, the beam source 11 should meet all requirements applicable to a DIAL light source, i.e. a light source by which the DIAL method is to be performed, with a sufficient pulse energy and a corresponding mean power having a sufficiently high pulse duration, an appropriately high pulse repetition frequency and only a low beam divergence. Such beam source could be:

1) A continuously tunable laser, in which dyestuffs or solid body materials are used as laser-active medium. In this case, possible solid body materials are, for example: Ti:Sapphire (Ti:SA), Cr^{3+}-doped and Cr^{4+}-doped materials such as alexandrite, colquiriite structure crystals such as Cr^{3+}:$LiSrAlF_6$ or Cr^{3+}:$LiCaAlF_6$) or forsterite. In addition, colour centre crystals are also suitable.

2) A light source based on the principle of non-linear frequency conversion, such as an optical parametrical oscillator (OPO). In that case, for example, the following materials are appropriate: beta barium borate (BBO), lithium-triborate (LBO), potassium titanyl phosphate ($TiOPO_4$ KTP), $KTiOAsO_4$ (KTA), $RbTiOAsO_4$ (RTA), $CsTiOAsO_4$ (CTA), potassium niobate ($KNbO_3$), lithium niobate ($LiNbO_3$), silver gallium selenide ($AgGaS_2$), and zinc germanium phosphate ($ZnGeP_2$). Other crystals, for example organic crystals, can also be used.

In similar manner to the beam source 11, the seed source 10 should be able to be tuned in the region of the absorption lines of the gas to be examined. In this case, the line width must be smaller or lie in the same order of magnitude as the width of the absorption lines. This means that a continuously operated or pulsed laser or an optical parametric

oscillator (OPO) could be used. All forms of light source mentioned in the preceding in connection with the beam source 11 can be used as the laser-active or non-linear optical material. Semiconductor lasers or laser systems, the active material of which is semiconductor crystals, can also be used. If an optical parametric oscillator is used as the beam source, it is particularly advantageous that the injection seeding can take place on both the signal wavelength and the idler wavelength of an OPO.

The switch 12, which is provided in the transmitter 1 and is arranged between the seed source 10 and the beam source 11, serves to interrupt injection seeding in order to thereby switch the beam source 11 between seeded, thus narrow-band, operation and unseeded, thus wide-band, operation. By means of the switch 12, the beam of a seed laser used as seed source 10 is interrupted or deflected. In this case, the switching can be effected in mechanical manner or with the aid of electro-optical or acousto-optical methods. If the manner of function of the injection seeding is dependent on polarisation, the injection seeding can then be interrupted by a rotation of the polarisation of the seed radiation.

Moreover, a narrow-band filter is frequently used in the receiver for carrying out DIAL measurements, which filter transmits to the detector only radiation situated in a small spectral range around the wavelength of the transmitter. Through the use of such a filter, solar background radiation is reduced and gas concentrations can be ascertained, with only small errors, in daylight. It is only necessary to take care that the transmission curve of the filter permits the transmission of the unseeded, thus the wide-band, radiation.

In an embodiment of an aircraft-borne DIAL system for water vapour detection in the atmosphere, a seeded OPO is used as the beam source 11 for the on-line measurements and the same OPO, but unseeded, is used for the off-line wavelength. BBO was used as a non-linear crystal in the OPO and the OPO was furthermore excited by the radiation, tripled in frequency, of a quality-switched Nd:YAG laser. A pulsed dyestuffs laser was used as the seed source 10 at a wavelength of about 620 nanometres.

The measurements were performed at the idler wavelength of the OPO of 828.2 nanometres. The seeded and thus narrow-band OPO was tuned exactly to the line centre of the selected H_2O transition with the aid of a photo-acoustical absorption cell for these measurements. For the off-line measurement, the seed source was mechanically blocked and the unseeded and thus wide-band OPO radiation was emitted without further elements limiting the bandwidth.

The Lidar echoes were collected by a 35 centimetre Cassegrain telescope and detected by an avalanche photo-diode (APD). A 5 nanometre (HWHM - Half Width at Half Maximum) filter was used for the suppression of background light. With the aid of rapid data detection, the signals could be displayed digitallly in dependence on the transit time. Apart from this equipment, a conventional DIAL method was used, in which the seed source is tuned between the on-line and the off-line travel length, as evident from, for example, Fig. 5.

A water vapour profile measured by the equipment and a profile measured in a conventional DIAL method are reproduced in Fig. 2. In Fig. 2, the H_2O mixture ratio in grams per kilograms is entered on the abscissa and the distance in metres is entered on the ordinate. The measurement obtained with the use of the equipment embodying the

invention is indicated by a dashed line and that obtained by the conventional DIAL method is indicated by a solid line. In this case, a close agreement of the two measurements is apparent.

Fig. 2 also shows measurement points for comparison. These are marked by triangles or solid circles and have resulted with two radius probe ascents which have taken place in the same time span as the measurements reproduced by the chain-dotted and solid lines, respectively.

The close agreement of the measurement results shown in Fig. 2 confirms the effectiveness of the method exemplifying and equipment embodying the invention. The differential absorption cross-sections are only relatively insignificantly different from the two measurement methods. This is evident, in particular, when the effective absorption cross-sections in the spectral range concerned are computed by means of equation (2). For the conventional case, Fig. 5 shows a value of

$$\Delta\sigma_{old} = 6.51 \cdot 10^{-23}\ cm^2,$$

whereas for the method exemplifying the invention Fig. 2 shows a value of

$$\Delta\sigma_{new} = 6.34 \cdot 10^{-23}\ cm^2.$$

In the above, the values given by the conventional method and by the new method are distinguished by the suffices "old" and "new".

In Fig. 3a, an unseeded and thus wide-band radiation was used for the off-line measurement in the example of a water vapour spectrum in the spectral range of 828 nanometres. In Fig. 3b, the seeded and thus

narrow-band light source was similarly tuned to the absorption line in the water vapour spectrum in the spectral range of 828 nanometres. In this case, the spectral bandwidth (FWHM - Full Width at Half Maximum) of the unseeded beam source is 2 nanometres and is thus greater by a factor of 1000 than the width of the beam source in the seeded operation, which is 0.002 nanometres.

For the computations, a Gaussian line profile with a half-value width of 2 nanometres was assumed in the case of a wide-band OPO according to Fig. 3a. The wavelength in nanometres is again entered on the abscissa and the absorption cross-section [1E - 22 centimetres^2] is entered on the ordinate in Figs. 3a and 3b. The ascertainment of the H_2O absorption cross-sections in the corresponding spectral range is based on the line parameters of the HITRAN data bank. A Lorenz profile, which is a good approximation for measurements at ground level, was assumed as line profile. The spectral half-value width of the seeded OPO was measured and is smaller than 0.002 nanometres. The spectral width of the wide-band unseeded idler radiation of the OPO usually amounts to 1 to 3 nanometres for the wavelength used. Model computations with different laser line widths from 0.5 to 5 nanometres in this spectral range have shown that the maximum change of the absorption cross-section $\Delta\sigma_{new}$ indicated above is less than 1%.

The afore-described method exemplifying the invention was tested in remote survey of water vapour on the ground. Due to the compactness of the equipment used, an aircraft-borne system is now possible for use in meteorlogical measurement programs. The method can be extended to all trace gases which are accessible to the DIAL detection technique and have a discrete oscillation rotation band system in the corresponding spectral

range, thus for example So_2, CO_2, NO_x and hydrocarbon compounds.

CLAIMS

1. A method for remote survey of trace gases, comprising the steps of a) determining the particle number concentration N(R) of a gas to be examined as a function of distance ($R = R_1 + \Delta R/2$) by means of the Differential Absorption Lidar (DIAL) equation:

$$\overline{N}(R) = \frac{1}{2 \cdot \Delta\sigma \cdot \Delta R} \ln \frac{P_{off}(R_2) P_{on}(R_1)}{P_{on}(R_2) P_{off}(R_1)}$$

wherein ΔR is the distance interval from the difference between two distances R_1 and R_2, $P_{on}(R_1)$, $P_{off}(R_1)$, $P_{on}(R_2)$ and $P_{off}(R_2)$ are the powers of backscatter signals received from the distance R_1 and R_2, and $\Delta\sigma$ is the effective differential absorption cross-section calculated as

$$\Delta\sigma = \frac{\int_0^\infty \sigma(\upsilon)[L(\upsilon - \upsilon_{on}) - L(\upsilon - \upsilon_{off})]d\upsilon}{\int_0^\infty L(\upsilon)d\upsilon}$$

wherein ν is the frequency of a selected spectral line of the gas, on is the frequency of the absorption line thereof, ν_{off} is a reference frequency, $\sigma(\nu)$ is the molecular absorption cross-section and $L(\nu)$ is the spectral energy distribution of a radiation source,

b) producing the power value P_{on} by means of radiation of a narrow-band radiation source with the absorption line frequency ν_{on} of the gas, the spectral width of the narrow-band source being less than the line width of the absorption line, and

c) producing the power value P_{off} by radiation of a wide-band radiation source of the reference frequency ν_{off}, the spectral width of the wide-band source being greater by a multiple than the line width of the

absorption line.

2. A method as claimed in claim 1 and substantially as hereinbefore described with reference to the accompanying drawings.

3. Equipment for carrying out the method claimed in claim 1, comprising transmitting means of variable spectral band width, the transmitting means comprising a seed source, a radiation source and switching means arranged therebetween and operable to switch the radiation source between seeded, narrow band operation for delivery of radiation at the absorption frequency and unseeded, wide band operation for delivery of radiation at a reference frequency, and receiving means for receiving backscatter signals from two distances.

4. Equipment as claimed in claim 3, wherein the radiation source comprises a continuously tunable laser in which dyestuffs or solid body materials are used as laser-active medium.

5. Equipment as claimed in claim 2, wherein the radiation source comprises a light source with non-linear frequency conversion.

6. Equipment as claimed in claim 5, wherein the radiation source is an optical parametric oscillator.

7. Equipment as claimed in any one of claims 3 to 6, wherein the seed source is a continuously operated or a pulsed laser.

8. Equipment as claimed in any one of claims 3 to 6, wherein the seed source is a continuously operated or pulsed optical parametric oscillator.

9. Equipment as claimed in claim 6 or claim 7 or 8 when dependent on claim 6, wherein the wavelength of the seed source corresponds with the signal wavelength or idler wavelength of the oscillator.

10. Equipment as claimed in any one of claims 3 to 9, the switching means comprising a mechanical switch means which for the interruption of injection seeding switches the radiation source between seeded and unseeded operation.

11. Equipment as claimed in any one of claims 3 to 9, the switching means comprising an electro-optical or acousto-optical switch for deflecting the beam of the seed source.

12. Equipment as claimed in any one of claims 3 to 10, the switching means being operable to vary the direction of polarisation of the seed source and thereby switch the radiation source between seeded and unseeded operation.

13. Equipment substantially as hereinbefore described with reference to Fig. 1 of the accompanying drawings.

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The Patent Office

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Claims searched:	All	**Date of search:**	9 June 1997

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Databases searched:

UK Patent Office collections, including GB, EP, WO & US patent specifications, in:

UK Cl (Ed.O): G1A (ACDD, ACDG, ABAX); H4D (DLAA, DLAB, DLX)

Int Cl (Ed.6): G01N 21/31, 21/35, 21/37, 21/39, 21/53; G01S 17/88

Other: Online database: WPI

Documents considered to be relevant:

Category	Identity of document and relevant passage	Relevant to claims
A	EP0270862 A2 (COMMISION of EUROPEAN COMMUNITIES)	

X	Document indicating lack of novelty or inventive step	A	Document indicating technological background and/or state of the art.
Y	Document indicating lack of inventive step if combined with one or more other documents of same category.	P	Document published on or after the declared priority date but before the filing date of this invention.
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